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AN EVALUATION OF THE COMPLEX TERRAIN DISPERSION MODEL AGAINST LABORATORY OBSERVATIONS: NEUTRAL FLOW OVER 2-D and 3-D HILLS

by

David G. Strimaitis[1] and William H. Snyder[2]

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EPA Project Officer
William H. Snyder

[1]Sigma Research Corporation, Lexington, MA 02173

2Atmospheric Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711. On assignment from the National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce.

ATMOSPHERIC SCIENCES RESEARCH LABORATORY
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16. ABSTRACT

A comparison is made of the predictions of the Complex Terrain Dispersion Model (CTDM) with wind-tunnel observations of flow and diffusion in a simulated neutral atmospheric boundary layer over two- and three- dimensional hills. The measure used to evaluate the ability of the model to simulate the laboratory data is the terrain amplification factor, defined as the ratio of the maximum ground-level concentration occurring in the presence of the terrain to the maximum that would occur (irrespective of position) due to the same source located in flat terrain. In general, CTDM predicted considerably smaller terrain amplification factors than were measured in the wind tunnel. When the measured values of flow speed-ups and streamline deformations were input to CTDM, the predictions of terrain amplification factors improved substantially. These results suggest the need for an adequate representation of the flow field around the terrain, and that substantial improvements in model performance may require computation of actual streamline patterns for calculating the strain along the flow trajectory, as opposed to a simple "relaxation" of the strain factors away from the hill crest as is currently done.

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An Evaluation of the Complex Terrain Dispersion Model Against Laboratory Observations: Neutral Flow Over 2-D and 3-D Hills

David G. Strimaitis

Sigma Research Corporation
Lexington, Massachusetts 02173

William H. Snyder[1]

Meteorology and Assessment Division
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

1. INTRODUCTION

This paper presents a comparison of Complex Terrain Dispersion Model (CTDM) predictions with laboratory observations of flow and diffusion over a two-dimensional hill and an axisymmetric three-dimensional hill placed in a simulated neutral atmospheric boundary layer. Although the focus of the model development effort has been on simulating plume/terrain interactions during stable rather than neutral flow, neutral flow is a legitimate limit for the formulations contained in the portion of the model that provides estimates of ground-level concentrations (GLC's) due to plume material that is able to surmount a hill rather than pass around it. These comparisons primarily test modeling assumptions about how the presence of the hill alters the straining in the flow and the turbulence in the flow; and how these properties alter ground-level concentrations.

The measure used to evaluate the ability of the model to simulate the wind tunnel data is the terrain amplification factor (TAF). This is defined as the ratio of the maximum GLC occuring in the presence of the terrain to the maximum GLC that would occur due to the same source located in flat terrain. As such, the TAF quantifies the degree to which a hill is able to alter the peak GLC that may be expected from a particular source.

2. THE DATA

The hills used in this study are (a) Axisymmetric Cinder Cone Butte (ACCB), an idealized version of CCB, and (b) Russian Hill 5 (RUSHL5), a two-dimensional ridge. The shape of the ACCB model is a fourth-order polynomial; its height is 155 mm, its maximum slope is 24°, and its base diameter is approximately 1.6 m. RUSHL5 is specified through a parametric equation; its height is 118 mm, its maximum slope is 16°, and its base length is approximately 1.2 m. Its shape is approximated in CTDM using a fourth-order polynomial.

In the wind tunnel, both hills were covered with fine gravel (3 mm) and the skirts were blended smoothly into the flat rough surface upstream and downstream. The hills were immersed in simulated atmospheric boundary layers approximately 1 m deep. The assumed scale ratio of 1:1000 translates into a 1 km deep neutral atmospheric boundary layer.

The boundary layer structure over the flat terrain (in the absence of any hills) was established through measurements of mean velocity profiles and turbulence intensities. The dispersive characteristics of the boundary layer were established through measurements of concentration profiles downwind of sources of various heights. Neutrally buoyant effluent was emitted from porous-ball stacks so as to avoid ambiguities associated with plume rise. Through these measurements, maximum ground-level concentrations in flat terrain were tabulated for each stack height.

To characterize hill effects, a hill was placed in the tunnel, the stack was positioned at some particular location (height and upstream distance), and the maximum GLC in the presence of the hill was measured and tabulated. That maximum may have occurred anywhere - upstream, on, or downstream of the hill. The terrain amplification factor was

[1] On assignment from the National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce

then calculated as defined above.

Figure 1 shows a portion of the map of the TAF's measured in the wind tunnel. Notice that for upstream sources, hill effects are much more prominent for three- rather than for two-dimensional hills. Note also that "excess concentration" is simply TAF - 1. Thus, the 3-D hill produces largest excess concentrations of around 200% for this matrix of source locations, whereas the 2-D hill produces much smaller effects, i.e., excess concentrations of around 80%. More detailed results of the study are contained in Lawson and Snyder (1985).

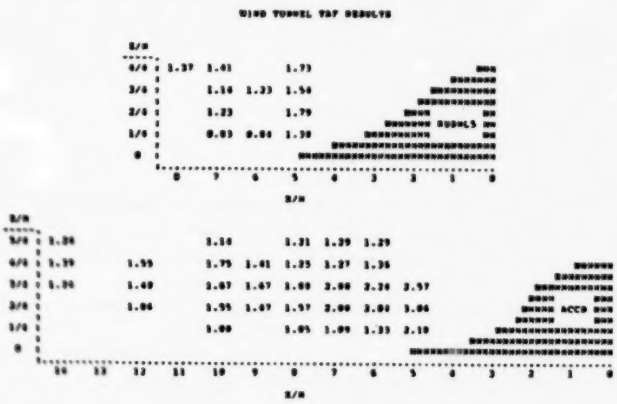

Figure 1. Map of TAF's Measured in the Wind Tunnel

3. THE MODEL

CTDM is a point source plume model for estimating dispersion over an isolated hill or separable hill segment. A central feature of CTDM is its use of a critical dividing-streamline height (H_c) to separate the flow into two discrete layers. Above H_c, the approach flow has sufficient kinetic energy to transport a fluid parcel up and over the hill, against the density gradient of the ambient stratification. Below H_c, the flow is constrained in a nearly horizontal plane.

The portion of CTDM that is evaluated in this paper is the portion responsible for calculating GLC's for the layer above H_c. In this layer, terrain-induced modifications to the plume arise from the distortion of the flow over the hill. Adjacent streamlines are deflected by differing amounts, which in turn changes the spacing between streamlines and hence, causes changes in the local speed of the flow. As a result, the plume trajectory is curved, the plume distorts so that it is thinner in the vertical direction and wider in the lateral direction, the turbulence statistics vary, and as shown in Hunt and Mulhearn (1973), turbulent diffusion across streamlines is enhanced by the contraction in the distance between streamlines in the vertical direction, and retarded by the expansion in the distance between streamlines in the lateral direction.

The GLC is computed as:

$$C(s,y_R,\theta;s_o) = \frac{Qe^{-0.5\left[\frac{y_R/T_1-y_r}{\sigma_{ye}}\right]^2}}{\sigma_{ye}\sigma_{ze}u}\, e^{-0.5[z_r/\sigma_{ze}]^2}$$

where

$$\sigma_{ze}^2 = \sigma_{zo}^2+\sigma_z^{*2}/T_z^2 \quad , \quad \sigma_{ye}^2 = \sigma_{yo}^2+\sigma_y^{*2}/T_y^2$$

Note that the plume is released at (θ,y_r,z_r), that the effective size of the plume over the hill is denoted by σ_{ze} and σ_{ye}, that the actual plume size at the upwind base of the hill ($s=s_o$) is denoted by σ_{zo} and σ_{yo}, and that the additional growth of the plume beyond s_o in the absence of the hill is denoted as σ^*. T_1 and the corresponding factor t_h are factors denoting the hill-induced change in the lateral and vertical spacing of streamlines, and T_y and T_z are factors for the resultant changes to the rate of plume growth (across adjacent streamlines) in the deformed flow.

This equation differs from the simple flat terrain Gaussian plume equation only in the appearance of a distortion factor T_1 in the lateral distribution term and in the appearance of effective plume spread parameters. Aside from the lateral shift in the impact region on the terrain, the influence of the terrain is exhibited only through changes in the rate of effective plume growth. When T_z is less than unity (this is generally the case), σ_{ze} exceeds σ_z at s and thus more plume material may lie "nearer" the surface.

In the version of CTDM evaluated here, T_1 and T_h are obtained from potential flow computations for an ellipsoidal hill-shape. The factors are computed at the crest, and are assumed to "relax" to unity with distance from the crest. The scale for this relaxation is approximately that of the hill itself. T_y and T_z are computed in a manner consistent with Hunt and Mulhearn (1973), with simplifications appropriate for hills of low slope. Turbulence intensity in the vertical is assumed constant along a streamline, so that σ_w is proportional to the wind speed. This is consistent with "inner layer" turbulence theory.

The vertical and horizontal spread parameters σ_z and σ_y used in CTDM are appropriate for stable-to-neutral conditions. Both have the form

$$\sigma = i\, u\, t/(1+0.5t/t_L)$$

where i is the intensity of turbulence. For

σ_y, the Lagrangian time scale t_L is specified by the modeler or is estimated from turbulence measurements for 5-minute and 1-hour periods, when these data are available. In general, t_L is large enough that σ_y grows linearly with time. For σ_z, t_L is given by Venkatram et al. (1984)

$$\frac{1}{t_L} = \frac{\sigma_w}{\Gamma z} + \frac{N}{\gamma^2}$$

where Γ and γ^2 are approximately equal to 0.36 and 0.27, respectively, and N is the Brunt-Vaisala frequency. For the wind tunnel simulations evaluated here, N is zero.

4. RESULTS

Meteorological data needed to run CTDM are taken directly from the wind tunnel measurements. Wind speed and σ_w are measured at the elevation of each source in the matrix. However, σ_v is obtained from a single turbulence intensity found by fitting the observed σ_y data obtained for several source heights in the absence of the hill. This method is used because the lateral distribution of GLC is observed to be virtually independent of source height. The data suggest i_y is about 14%, and t_L is 400m/u. Using these parameters, TAF's produced by CTDM for both hills are shown in Figure 2.

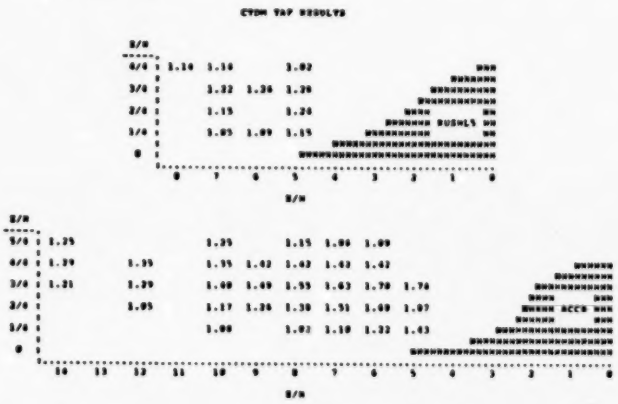

Figure 2. Map of TAF's Predicted by CTDM

For the 2-D hill, CTDM produces a maximum increase in GLC of 28% which is about a third of the 79% increase observed in the wind tunnel. For the 3-D hill, CTDM produces a maximum increase in GLC of 87% which is less than half the 206% increase observed in the tunnel. In both instances the "window" of greater TAF's produced by CTDM is similar to that observed. But note that the TAF's for the greater source heights tend to apply to receptors to the lee of the crest. With no wake algorithm in CTDM, discrepancies for these source heights are expected.

Because the effect of terrain on GLC's produced by CTDM in the neutral limit is primarily driven by deformation in the flow and the concurrent changes to the turbulence, estimates of T_l, T_h, and T_u (the speed-up factor) obtained from wind tunnel observations have been compared with those computed in CTDM. Note that $T_l * T_h * T_u = 1$. For the 2-D hill, any changes in streamline spacing in the vertical are inversely proportional to changes in the speed of the flow. T_u measured at the crest of the hill is 1.48, but the value used in CTDM is 1.30. This difference is thought to be the result of there being shear in the neutral boundary layer, while the flow model in CTDM assumes a uniform approach flow. The increase in wind speed at the crest implies that streamline spacing in the vertical is 87% of that assumed in CTDM.

For the 3-D hill, any change in the speedup of the flow at the crest is not simply reflected in the vertical strain. Plume cross-section data reported by Snyder and Lawson (1986) for tracer released 6 hill-heights upwind of the 3-D hill at an elevation equal to half of the hill height indicates that T_h is 0.42. CTDM uses a value of 0.55. Therefore the observed streamline spacing is 76% of that used in CTDM. Analysis of data for tracer released at an elevation approximately equal to 1.25 hill-heights indicates the spacing is 77% of that used in CTDM. The observed speedup of the flow over the crest indicates that T_u equals 1.37, a factor of 1.114 times T_u used in CTDM. The lateral strain factor is not observed directly, but the measured width (σ_y) of the plume both with and without the hill in the tunnel is used to check the validity of setting it equal to $1./T_u * T_h$. The ratio of σ_y(hill) to σ_y(flat) for the plume released at half the hill height is observed to be 1.42. When CTDM is run with the observed values of T_u and T_h for this particular source location (and $T_l = 1./T_u * T_h$), the ratio of the calculated values of σ_y equals 1.37 which is quite close to the observed ratio.

The assumption that the turbulence intensity in the vertical is constant in the deformed flow was also evaluated. Measurements of turbulence upwind of and over the crest of the 3-D hill show that i_z does remain constant in the lower part of the boundary layer and is virtually constant at greater heights.

Figure 3 shows the TAF's produced by CTDM when the T-factors for the flow are scaled to agree with those obtained from the wind tunnel measurements. The terrain effect produced by the model has substantially improved. The greatest TAF for the 2-D hill has increased from 1.28 to 1.48 (61% of the observed excess concentration) and that for the 3-D hill has increased from 1.87 to 2.39 (67% of the observed excess concentration).

Furthermore, TAF's at many locations are in near agreement. Still, there remains a tendency toward underestimating TAF's for sources just upwind of the hill near an elevation of half the hill height.

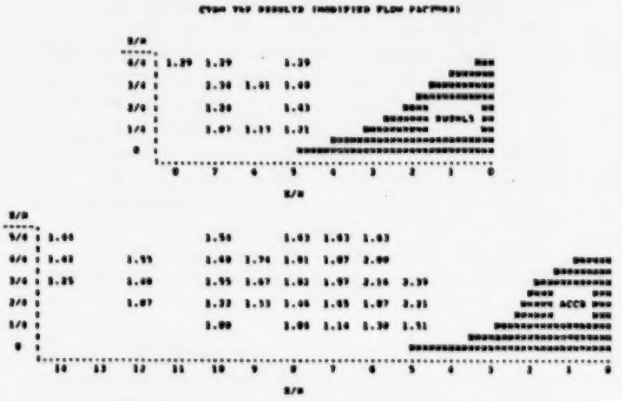

Figure 3. Map of TAF's Predicted by CTDM When Using the Observed Flow-Field Factors

5. CONCLUSIONS

This comparison of modeled and observed TAF's for sources upwind of a 2-D and a 3-D hill demonstrates the need for an adequate representation of the flow field around the terrain. Substantial improvement in modeling the terrain effect was obtained when the strain inferred or measured over the crest of the hills in the wind tunnel was used in the calculations. Further improvement in the performance of the model may require the computation of actual streamline patterns for calculating the strain in the flow along the trajectory, rather than a simple "relaxation" of the strain factors away from the crest. Work is currently underway to incorporate flow-field computations in CTDM.

6. ACKNOWLEDGEMENTS

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